Identification of Failure Root Causes Using Condition Based Monitoring in Solid Insulations

A thesis submitted in partial fulfilment of the requirements for the award of the degree of

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in

Power Electronics & Drives

by

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CERTIFICATE

This is to certify that the thesis entitled, “Identification of failure root causes using condition based monitoring in solid insulations” submitted by Soumya Mishra (Roll No.213EE4328) in partial fulfilment for the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in “Power Electronics and Drives” during 2013-2015 at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University /Institute for the award of any degree or diploma.

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CONTENT

ABSTRACT

Most of the high voltage (HV) power equipment is made up with solid insulation like paper insulation, glass insulation, epoxy insulation etc. Among all the insulation material the paper insulation is the most ancient type of insulation used in cable and nowadays the commonly used insulating material is Cross linked Polyethylene (XLPE). The presence of impurities in the insulation system is one of the root causes of insulation failure as they are form a weak zone inside the healthy insulation system. Therefore, early identification of degradation process like formation of electrical tree structures inside such solid electrical insulation due to high voltage tress during its operating life is utmost requirement to prevent the electrical power equipment from a sudden and complete insulation failure. To study the growth mechanism of electrical tree structure inside the insulation with different applied high voltage a commonly used insulating material like XLPE and paper insulation in HV power cable are consider for this present work. This work also describes the ageing process by conducting the partial discharge (PD) test on the same insulating materials. Finally, the effect of PD on insulation i.e., formation of electrical tree structure on solid insulation was observed by using Scanning Electron Microscope (SEM) and analysed.

LIST OF ABBREVIATION

Abbreviation	Acronyms
PD	Partial Discharge
HV	High Voltage
EHV	Extra High Voltage
XLPE	Crosslink polyethylene
SEM	Scanning electron microscope
FESEM	Field emission scanning electron microscope

LIST OF SYMBOL

Symbol	Name of symbol
E	Electric field
V	Applied voltage
d	Distance between the two electrodes
r	Needle tip radius

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

- INTRODUCTION
- LITERATURE REVIEW
- MOTIVATION AND OBJECTIVE
- ORGANIZATION OF THE THESIS

CHAPTER-1

1.1. INTRODUCTION

Power cable is a very essential tool in electrical systems for the transmission and distribution of electrical power. These power cables are assembly of some conductors bundled together covered with insulating material and protective jackets. The insulation is either made up of thermoplastic compound, thermosetting compound or paper. Paper based insulation is the oldest insulation type which is still in application for high voltage cables. The other widely used material for high voltage power cable insulation is cross linked polyethylene. This material has different polyethylene chain linked together which prevents the material from melting at relatively high temperature. Ageing of an insulation start just after it is being manufactured. In a new system electrical insulation should be good and healthy. With time the insulation system undergoes through various electrical, mechanical and chemical effects which may lead it to failure.

Partial discharge is the leading cause of break down in solid insulating system. In medium voltage underground cables, pre brake down gas filled channels may incepts from defective region even at a normal operating voltage. Micro voids and contaminating particles inside the insulating material are the potential source of partial discharge which results the formation of electrical trees continuing the degradation process and ultimately leading to break down of the insulation. A current pulse having rise and fall time around less than 1ns is injected inside the insulation due to the effect of partial discharge. This partial discharge signals can be identified using acoustic sensor or by the use of a coupling capacitor.

Therefore in this work, an experimental study was carried out on oil-paper insulation and XLPE cable insulation, during testing the emitted PD signals were observed and saved. Since the insulations tested here are not transparent, it is not possible to visualise the tree growth inside it. Scanning electron microscope (SEM) plays a great role to study the degradation process and growth characteristics of electrical tree. To know the stability of use for a specific insulating material and to get a better understanding of the insulator's ageing phenomenon, to estimate the remaining life of the insulator, to check the quality and its dependability on various factors it is very essential to conduct diagnostic tests before putting the insulation into operation.

1.2. LITERATURE REVIEW

In the most recent years high voltage power equipment are extensively used for transmission and distribution of electrical power. Installation of underground cable system brought a revolution in power system framework by maintaining a stable and uninterrupted power supply. But the breakdown of insulator is the prime cause of power failure. From the oldest oil paper insulation to the newest XLPE cable insulation, development of electrical tree due to partial discharge activity is the destructive hotspot for solid insulation degradation [1]-[3]. Partial discharge activity occur inside solid insulation due to the presence of solid, liquid or gaseous contaminants present inside it. No matter with how much care the insulation is manufactured but some impurities will always remain inside it during the curing process. So PD activity can be reduced by using insulation of high quality but it can’t be avoided totally [4]-[7]. A. El-Zein have proposed a model for examining the electrical tree development in solid dielectric medium utilizing a needle plane electrode. The solid insulation is mounted between the needle and the plane electrode. Tree shape characterized be dependent upon the electric field strength. They have exhibited a model for re-enacting electrical tree development in a three dimensional field [8]-[9].In solid polymeric cable insulations growth of electrical tree takes place in a stepwise manner. Degree of branching is very less at the initial stage but more number of parallel branches develop before the tree reaches the ground electrode [10]-[12].

Quality requirements are increasing and condition based monitoring is becoming more useful for quality assessment. R. Sarathi, A. Nandini and Michael G. Danikas an endeavour has been made to recognize the partial discharges created because of the beginning and propagation of electrical trees receiving UHF method. [13]. L. A. Dissado, J. M. Alison, J. V. Champion, S. J. Dood and P. I. Williams had given a report on The Propagation Structures of Electrical Tree in Solid Polymeric insulation. They have given two interchange methodologies to electrical tree propagation as per stochastic model that ascribe of tree structures to irregular probabilistic elements and in release avalanche model field variances are capable. It has been inferred that both models give the fractal structures of tree [14].

S. Mohanty *et*.al. described the procedure adopted for condition based monitoring of paper insulation both at AC and DC conditions[15] . Different methods of analysis are proposed to study the damage on insulation papers under high voltage and to observe the behaviour of leakage current due to partial discharge [16]-[22].

1.3. MOTIVATION

Reliability of any electrical system depends on the insulation system present in it. Though the insulating materials are manufactured with great care, still there are some impurities remain inside it which are the main cause to start partial discharge and electrical treeing process. So the study of insulating properties and dielectric behaviour and their dependence on various effects is essential. Electrical treeing is not just the prime variable influencing the quality of cross linked polyethylene (XLPE) and paper insulation, moreover it is responsible for the final destructive form of cable protection working in the long run.

1.4. OBJECTIVES

The whole project is subdivided into two parts, the first part is related to XLPE cable insulations and the second part to oil paper cable insulations. The main objectives of this work are:

- To study the growth mechanism of electrical tree in solid insulating materials.
- Observe the effect of voltage with time on paper insulation and cross linked polyethylene.
- Study the degradation process of paper insulation and XLPE insulation through electrical tests and measurements. The results are compared to identify the cable condition classes.

1.5. ORGANIZATION OF THESIS

The total project work is documented in this thesis in seven separate chapters which includes as follows

Chapter 1: This chapter comprises of the introduction, literature review, motivation and objective of the research work.

Chapter 2: This chapter discusses about the degradation process of polymeric cable insulation and oil paper insulation of medium voltage cable, it also describes the characteristic and uses of solid insulations and its degradation due to electrical tree and water tree.

Chapter 3: This Chapter shows different growth phases of electrical tree and the necessity of electrical trees detection in solid insulation, its classification and the effects of electrical treeing in solid cable insulation and also its growth characteristics.

Chapter 4: Includes the process of experimental setup development for the generation of electrical tree in XLPE cable insulation. The partial discharge signals were detected by using acoustic emission sensor connected to a CRO.

Chapter 5: In this chapter experimental setup is used for the generation of electrical tree in paper insulation by using needle-plate electrode arrangement, it also describes the step by step process of sample preparation and flashover phenomenon during breakdown.

Chapter 6: Gives idea about the tree inception voltage for a particular insulation distance and gives a comparative study between the degradation processes in Nomex and Manilex insulation paper.

Chapter 7: Finally this chapter concludes the project work and also discuss about the scope for future work briefly.

CHAPTER 2

XLPE AND OIL PAPER INSULATION OF MEDIUM VOLTAGE CABLE

- COMMERCIAL 33 KV XLPE CABLE
- CROSS LINKED POLYETHYLENE DEGRADATION
- WATER TREEING AND ELECTRICAL TREEING IN XLPE

CHAPTER -2

2.1. COMMERCIAL 33 kV XLPE CABLE

Cross-linked polyethylene (XLPE) insulated power cables are in use since the end of the 1960s. All the new installations and also the restoring operation of old underground cables are performed using XLPE-cables.

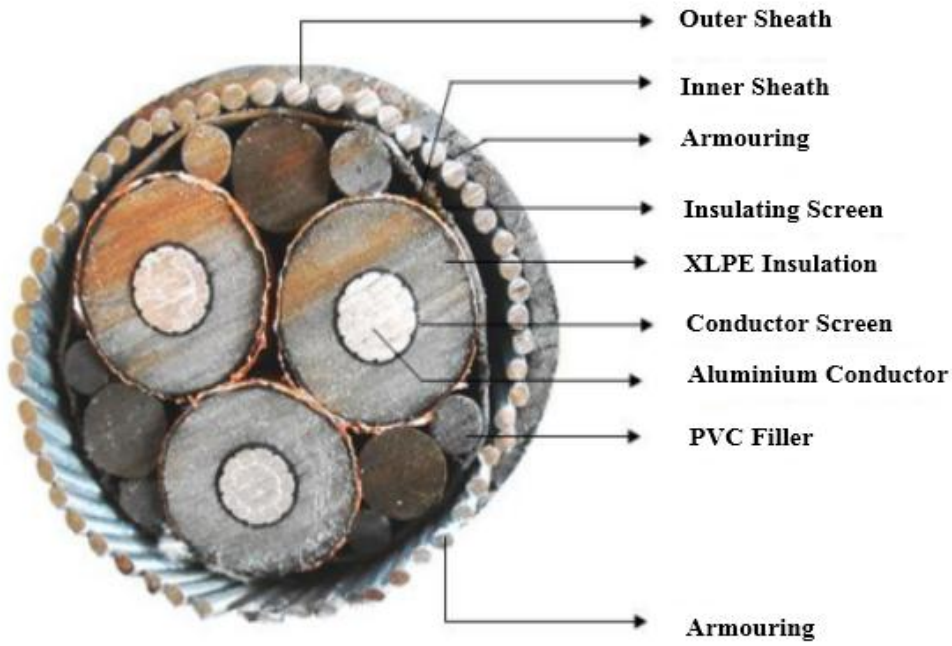


Fig. 1. Cross sectional view of 3 phase XLPE cable

Polyethylene (PE) is a thermoplastic semi-crystalline polymer widely used in the cable industry. It is produced by polymerization of ethylene (C_2H_4), and cross linking of ethylene gives rise to Cross linked polyethylene (XLPE). Cross linking renders PE infusible and suitable for service temperature up to 125^0C. Its resistance to cold flow and abrasion are superior to conventional PE, while its dielectric properties are comparable. Another advantage of crosslinking is that it makes possible higher filler loading without significant loss of physical properties. This is why XLPE cable has almost completely outclass compound filled cables in the medium voltage range. However the main difficulties of PE and XLPE insulations are their sensitive to partial discharge and the associated question of life time. Cavities of 1-30 µm are unavoidable during manufacturing and are potential source of commonly observed partial discharge activity.

2.2. DEGRADATION PROCESS OF CROSS LINKED POLYETHYLENE

The degradation process of XLPE cable insulation is categorised into two parts i.e. extrinsic degradation process and intrinsic degradation process. Extrinsic degradation process is mainly due to micro voids and contaminating particles present inside the insulating material, but intrinsic degradation is due to any change in physical or chemical property or due to the trapped charges. Intrinsic degradation is not confined to a local area but it effects a large mass of the insulation like chemical or thermal degradation influence the efficiency of a large area of cable. The structure of insulation is not even therefore some voids are always remain inside the material which are the prime cause of electrical degradation or partial discharge effecting a local area.

2.3. THERMAL DEGRADATION

- The temperature of XLPE cable insulation should maintained under 90 ºC during normal operation while up to 120 ºC during fault condition.
- A temperature increase beyond 225 ºC, gives rise to the trans-vinyl groups and this Formation indicates the radical rearrangements. At very high temperature, normally beyond 350 ºC the deprivation of polyethylene takes place by incomplete thermal cracking.

2.4. ELECTRICAL DEGRADATION

Electrical degradation is the most hazardous one which causes the most serious damage in solid insulation. The mechanism behind electrical treeing process is partial discharge. Electrical treeing is a random process which effect localised area of the insulator. The total breakdown of insulation is associated with a specific localised region.

2.4.1. WATER TREEING

Generally most of the cables installed underground are exposed to moistness in the soil hence prone to degradation due to water tree. These water tree often initiate and propagate inside XLPE insulation which is under high voltage stress and exposed to humidity. Risk of water tree initiation and the insulation failure fully depends upon the impurity content of the material. The insulation may in grace water from outside environment if there is absence of water blocking barriers outside the cable. Joints and terminations are the points where water enter in to cable insulation. The moisture which is conductive starts to spread in the path of electric field in form of a tree like structure. The existing water trees can be divided in to two types, vented and bow-tie. Bow-tie type water tree initiates from the impurities or voids present inside the insulation and likely to spread in two direction. Total length of these type of trees are within few some tens of μm. It is mostly seen in distribution cables however it does not have significant effect on degradation of cable. Small bow-tie water trees are also likely to form due to the residual moisture present after the cross linking process but these type of water trees are not thought to be dangerous. Vented water trees generally originate at the edge between the semi conductive screens and insulation and propagate in the direction of applied electric field. Initiation time of vented water tree is much more than that of the bow-tie tree. Bow tie trees are small in length and saturates after few μm but vented tree propagate up till it reach the ground, dividing the total insulation in to two parts. Thus these vented water trees are thought to be more harmful than the bow-tie trees. Initiation of a water tree may lead to localised damage due to stress enhancement. Water tree differs from electrical tree in the way that it do not necessarily form a prominent channel through the insulation. Water tree may apparently disappear when moisture and the applied electric field are removed. In some of the cases a cable can able to withstand the normal operating voltage even after the formation of water tree in the insulation. Initiation and growth of water trees depends on various factors like presence of water or moisture, frequency and intensity of applied electric field, the quality of insulation, mechanical stress and temperature.

2.4.2. ELECTRICAL TREEING

Electrical tree is the prime cause of insulation failure in polymeric cable insulation, a number of fine conductive channels propagating in the similar direction as the electric field collectively form electrical tree. Presence of micro cavities, voids or other contaminating particles present inside the insulation may cause the initiation of electrical tree inside the polymer if the applied electric field is large enough. Growth phases of electrical tree are divided in to three phases i.e. initiation phase, propagation phase and breakdown. Poly ethylene emits visible light when it is subjected to an AC voltage stress above a certain threshold voltage, due to the changes of positive and negative polarities injected inside the polymer. The UV light causes photo chemical reaction to occur which creates free radicals and break chemical bonds forming the first channel of electrical tree. During the propagation phase the main channel branched in to several other branches forming a tree like structure. Discharges of 5 pC are sufficient to cause thermal runaway and widespread local thermal degradation of the polymer. Propagation rate of electrical tree depends upon frequency and magnitude of applied electric field, environmental and mechanical stresses and temperature. Though the insulations are manufactured with great care still there are impurities remain inside it in the form of small cavities or bubbles, partial discharge process occurs inside the cavity when the electric field exceeds a threshold value. Partial discharge process may give rise to a number of positive ion and free electrons, these free electrons collide with other molecules to form electron avalanche and degradation of that insulation material start. The degradation process will be in the form of conducting channels known as electrical tree. Total breakdown will occur when the conducting channel will reach the ground electrode

2.5. CHARACTERISTICS AND ADVANTAGES OF USING XLPE IN HV SYSTEM

Outstanding Electrical and Physical Properties: XLPE has very good physical as well as electrical property, hence it is considered to be the best insulating material among all other insulations that are yet used as insulator in underground cable system.

Ability of Carrying Large Currents: An excellent ageing characteristic and temperature withstanding capability allow XLPE to withstand a temperature of 90 ^{o}C at normal condition and 125 ^{o}C at a fault condition.

Ease of Installation: XLPE is light in weight and the process of installation is easy and reliable, the termination method is simpler as compared to as compared to the other cables.

Free from Height Limitation and Maintenance: XLPE cables can be installed anywhere without taking in consideration of the route profile (height limitations) as it does not contain oil and is free from failures due to oil migration in oil-filled cables.

No Metallic Sheath Required: XLPE does not absorb water, hence no metallic casing required. For this reason it is free from metallic sheath failure such as corrosion or wear and tear of the casing.

CHAPTER 3

PARTIAL DISCHARGE AND ELECTRICAL TREEING PHENOMENON

- CONCEPT OF ELECTRICAL TREES
- PARTIAL DISCHARGE MECHANISM
- ELECTRICAL TREEING PHENOMENON IN XLPE
- GROWTH STAGES OF ELECTRICAL TREE
- TYPES OF ELECTRICAL TREE

CHAPTER -3

3.1. PARTIAL DISCHARGE MECHANISM

Partial discharge activity occurs in a cavity only when the electric field in the cavity exceeds the breakdown strength of the gas in the cavity. There must also be free electrons available to initiate an electron avalanche. Since the dielectric strength of air is much less than the solid insulation the air space breakdown electrically. An electric spark occurs in the air medium releasing considerable amount of energy. The electric field at which breakdown strength of the gas is exceeded is defined as cavity inception field and the voltage is called inception voltage.

When the electric field is higher than the break down strength of the gas and there is an electron available, then the electron will be accelerated by the applied electric field in the cavity and will interact with neutral gas molecules. If the energy of the accelerated electron is high enough it will ionize any gas molecule it will collide with, resulting in an increase in the release of new electrons, positive ions and heat and other by products in the cavity. This process is called ionization.

The recently generated free electrons collide with other gas molecules in the cavity and this process repeats. More free electrons are generated resulting in an increase in the number of free electrons. This repetition of gas ionization process is called “electron avalanche”. This electron avalanche will grow significantly in size until it forms channels in the cavity. The pattern of channels formed determines the type of discharges. During the avalanche process the temperature in the cavity increases due to heat energy released from ionization and this causes pressure in the cavity to increase.

3.2. ELECTRICAL TREEING PENOMENON IN XLPE

Electrical treeing is a process of pre breakdown ageing phenomenon due to pointed conducting or semiconducting particles or micro voids present in the extruded polymeric cable insulation during dry service conditions. Most often they occur in monolithic or extruded or cast polymeric materials. If there is a discontinuity in the body of a dielectric which is filled with a liquid or an electrolyte like water or its solutes, the tree formation is called electrochemical treeing. Both types of tree progresses and finally cause a disruptive breakdown of the dielectric.

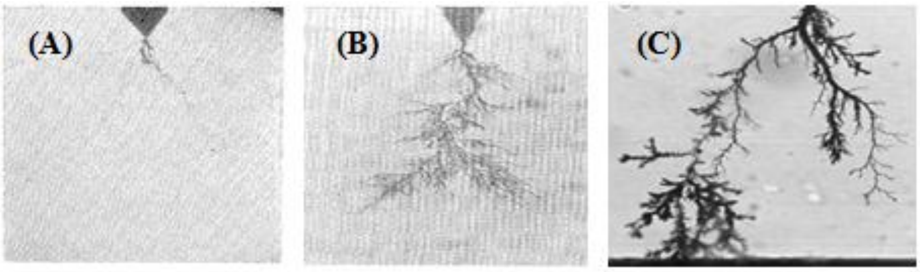


Fig. 2. Growth phases of Electrical tree (A) Initiation of Electrical tree (B) Propagation of electrical tree and (C) Break down occurred due to electrical tree in XLPE Growth phases of Electrical tree [16]

Trees are mostly initiated from discharging cavities. When polymeric cable insulation are subjected to high electrical stress, a localized degradation starts due to the partial discharge activity caused by contaminants or voids within the insulation. Formation of very small gas filled channels starts from the region of stress concentration which looks like a real "tree" and the processes are only due to electric field so the name "Electrical tree". Tree formation can be distinguished into three phases: Initiation, Propagation and Breakdown.

3.2.1. INITIATION OF ELECTRICAL TREES IN POLYMERIC CABLE INSULATION

Tree initiations caused by an extremely high electric field at the tip of an electrode producing divergent fields or by discharge in gas filled voids. Initiation of a tree can be known from the electro-luminescence which is seen before PD. The first branch of electrical tree is the result of a series of events. The injected charges are accumulated and at a certain voltage level it will force the polymer chain to breakdown. As a result of which damage inside the insulation starts in the form of a fine tubular structure. Electric field applied type of impurity or void size, mechanical properties of the material influence both initiation and propagation.

3.2.2. PROPAGATION OF ELECTRICAL TREE IN POLYMERIC CABLE INSULATION

The propagation stage is said to be started when discharge with a magnitude of 0.1 PC or higher can be detected the tubules or the branches that are formed during this stage are 5-10μ meter long and has a radius of 1 micro meter. According to the geometrical shapes electrical trees are mainly categorized into two types that is bush tree and branch tree. Discharge rates and fractal dimensions of both the trees are different.

3.2.3. BREAK DOWN PHENOMENON POLYMERIC CABLE INSULATION

Breakdown take place when channel resistance becomes sufficiently low, causing local heating and melting of the surrounding polymer, making the channels wider. With large number of voids possibility of breakdown increases. More will be the partial discharge, there will be more rapid growth of electrical tree. Therefore it is important to study the partial discharge activity and treeing characteristics in the insulating materials for the evaluation of its insulating status.

3.3. TYPES OF ELECTRICAL TREE

Depending upon the shape electrical trees are mainly divided in to two types i.e. branch type tree and bush type tree.

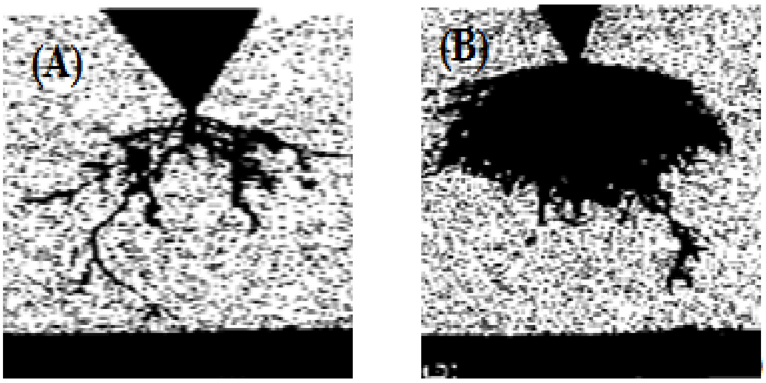


Fig. 3. Types of Electrical tree (A) Branch Type Electrical tree (B) Bush Type Electrical tree [12]

3.3.1. BRANCH TYPE TREE

Rate of propagation of branch tree is higher than that of other type of trees. It has a fractal dimension between 1 and 2. Branch trees are formed when the electric field applied is less. For these type of trees the channels become conducting due to the deposited carbon on the walls of the branches and it will suppress PD to occur inside the channel. So PD occur at the tip of the channel by resulting enough thermal energy to degenerate the insulation. In this way the branch tree extend in a step wise manner resulting break down of the material.

3.3.2. BUSH TYPE TREE

Rate of propagation is less than the branch tree. Fractal dimension is between 2 to 3. Bush tree formation occur when the voltage applied is very high. First channel of bush tree starts like the branch tree. Branching will carry on as a result of PD throughout the channel i.e. from the electrode tip to the end of the channel. This is due to the conducting particles on the channel wall. Branches are created by the large amount of charge on the channel walls which makes extension possible from the side

3.4. PAPER INSULATION

Generally almost all the insulation papers are manufactured within 65 to 155 g/m^2 weight range to eliminate the presence of hole inside it. Cellulose is the main constituent in all electrical insulating papers, which helps to increase the dielectric strength greater than one. Paper is hygroscopic in nature and hence it prevents any kind of leakage water to flow along the conductor.

3.5. APPLICATION OF PAPER INSULATION

3.5.1. CABLE PAPER INSULATION

Paper insulation is used both in telephone cable as well as high voltage power cables. As the telephone cables have less voltage then the power cables, thickness of the insulation paper used in telephone cables are more than that of the power cables.

3.5.2. HIGH VOLTAGE POWER CABLE PAPER

Due to the hygroscopic nature of paper it is extensively used in submarine power cables having a voltage more than 400 kV. Paper insulation swells up and prevent water from coming in contact with the conductor.

3.5.3. CAPACITOR TISSUE

Super fine thin tissue papers are used in capacitor. The wood pulp is thoroughly cleaned and not bleached to prepare paper within the weight range of 6-12 g/m^2.

3.5.4. TRANSFORMER BOARD

A transformer uses paper insulation to isolate the winding from core or from HV winding to LV winding. Insulation used for this purpose is called pressboard paper and has an insulation thickness of 8 mm or more.

3.6. OIL IMPREGNATED PAPER INSULATIONS USED IN CABLES

The ancient insulation types used in underground cables are the oil impregnated paper insulations. Some of the cables using oil-paper insulation are still in use. Insulation papers are mostly prepared from pulp of wood.

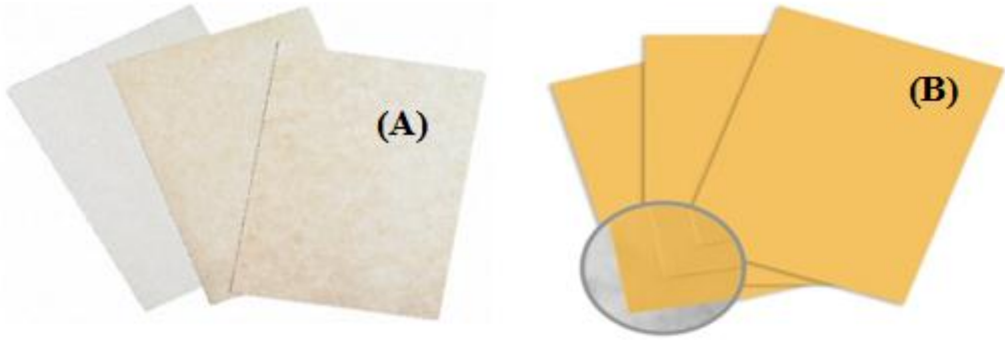


Fig. 4. Samples Of Oil Paper Insulation (A) Nomex Paper Insulation, (B) Manilex Paper Insulation

The formation of paper is started from wood in initial days. Glucose molecule links to one another in a special manner to form a polymer called cellulose, as shown in Fig. 5. Kraft paper's DP value is about 1100 - 1500, which means a single cellulose fibre consists of 1100 - 1500 glucose molecules. Lignin is selectively dissolved and removed through the chemical process, even though about 5 % always remains. Kraft paper contains of cellulose, residual lignin and hemicelluloses. Generally wood pulp is not bleached, but cautious washing is necessary to eliminate the ionic elements. The degradation performance of insulation paper is time taking which can be accelerated by thermal advancement. During thermal advancement dicyandiamide ether is linked to the OH-groups in the cellulose.

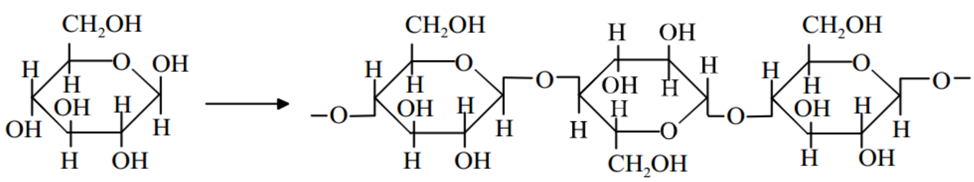


Fig. 5. Formation of cellulose polymer from glucose molecule

Strips of wide paper are wrapped around conductor of the cable. A small gap is always maintained between strips of paper. Then the succeeding layer of paper is enfolded on the former layer to avoid the creation of passages between the paper coatings. The width of the paper strips are kept between 50 to 200 μm and the thinnest are used nearer to the conductor. After the wrapping of the paper strips, the cables are vacuum treated and then air and moisture are removed through heat treatment. The insulation is emerged in mineral oil after the heat treatment. Oil impregnates the paper and the gaps between the layers of the paper are filled by oil. Oil-paper is not homogeneous because of its construction. In oil the electric field is about two times that of the strength of the electric field in paper.

3.7. DEGRADATION PROCESS OF OIL-PAPER INSULATION

There are some changes occur in the characteristics of oil paper throughout its life time. The variations are either due to ageing or because of external stresses. External stress can swift up the degradation process of insulating material strongly. The total stress on Electrical Cables is the sum total of different types of thermal, electrical and mechanical stresses subjected on it during the operation.one type of stress never acts alone. It is impossible to model the entire effect of all the dissimilar of stresses at a time.

Oil being an organic material is prone to chemical reactions in the presence of oxygen. The oxidised hydrocarbon molecules of oil form hydrogen peroxide which is a chain reaction. Then decomposition of Hydrogen peroxide form highly reactive free radicals. Free radicals then oxidise to form more new free radicals. Due to degradation different byproducts are formed out of the oil. The byproducts are conductive impurities, precipitates water and acids. Oilpaper cables which is a moisture blocker is also used in metallic sheaths.

In medium voltage oil impregnated paper insulation, water and acid causes hydrolytic degradation which then reduces the degree of polymerisation and it weakens the mechanical properties of paper. When carbon atoms are attacked by oxygen in the cellulose molecule, the process of oxidation occurs. Because of oxidation aldehydes, acids, carbon monoxide and water are produced. Bonding between cellulose molecules are weakened, causing a lower degree of polymerisation. This mechanism releases water which further contributes to hydrolysis. .

During normal operation i.e. below 140 °C, the effect of pyrolysis processes are of little relevance. Fig. 6 shows different degradation processes and the yield products from these. Degradation of paper mainly hampers its mechanical properties with minor change in its electrical properties. The degree of polymerisation of the paper insulation decreases during degradation. This is around 1100 to 1500 for a new paper, but the value is less than 500 after the paper is subjected to thermal degradation .cable failure occurs during short circuits because of the weakening of mechanical properties.

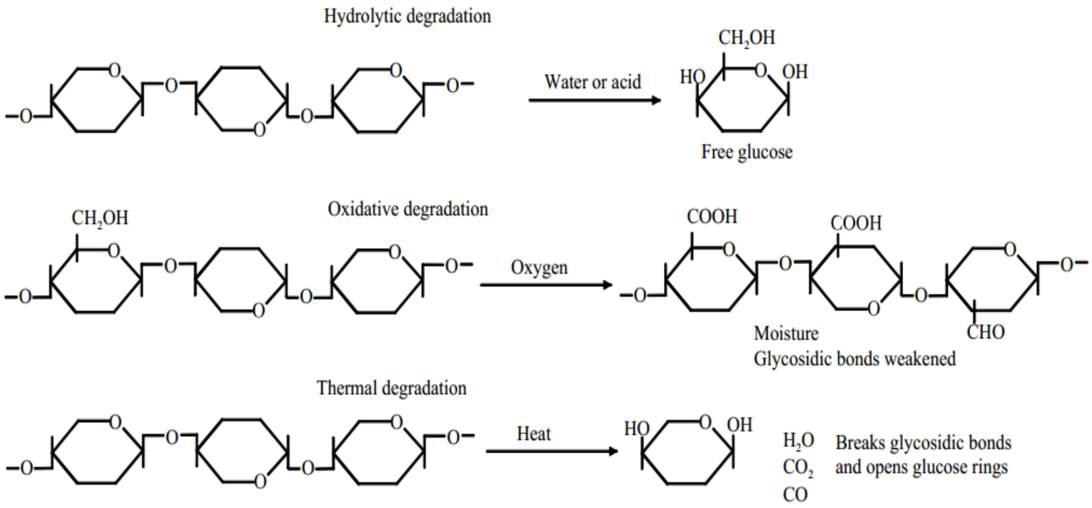


Fig. 6. Hydraulic, Oxidative and Thermal Degradation of cellulose

In cable insulation the space between insulation papers is filled with oil. Various types of gases are produced during the degradation of cables. They dislocate the oil and fill the gap between paper strips with gas filled cavities. Inside a gas filled cavity electric field strength is much more than that of the surrounding insulation. Partial discharge (PD) will occur when it exceeds the threshold or withstand level of the cavity. New gas filled cavities are formed due to PD along with carbon deposition on the wall of the insulation. The carbon particles tend to dissolve in oil which reduces its dielectric strength. Oil-paper insulation is partially self-healing with respect to PD phenomena. Partial discharges and gas filled cavities disappear when the oil moves and takes the place of gas in cavities. Sometimes mechanical stresses stimulate the inception of PDs.

CHAPTER 4

EFFECTS OF PARTIAL DISCHARGES ON XLPE CABLES: AN EXPERIMENTAL STUDY

- EXPERIMENTAL WORK DONE FOR THE GENERATION OF ELECTRICAL TREE
- SAMPLE PREPARATION USING XLPE
- PROCEDURE OF TESTING XLPE FOR ELECTRICAL TREE GENERATION
- DETECTION OF PARTIAL DISCHARGE BY ACOUSTIC EMISSION SENSOR
- ACOUSTIC EMISSION SENSOR
- PRINCIPLE OF PD DETECTION BY ACOUSTIC EMISSION TECHNIQUE

CHAPTER -4

4.1. SAMPLE PREPARATION USING XLPE CABLE

The abbreviated form of "cross-linked polyethylene" is XLPE. Polyethylene has a linear molecular structure. The chemical bond can be easily deformed at a high temperature, but in XLPE the molecules are cross-linked in a three dimensional network and not easily deformed even at a high temperature. Small dielectric loss is another quality of XLPE insulation for which it is extensively used in medium and high voltage cables.

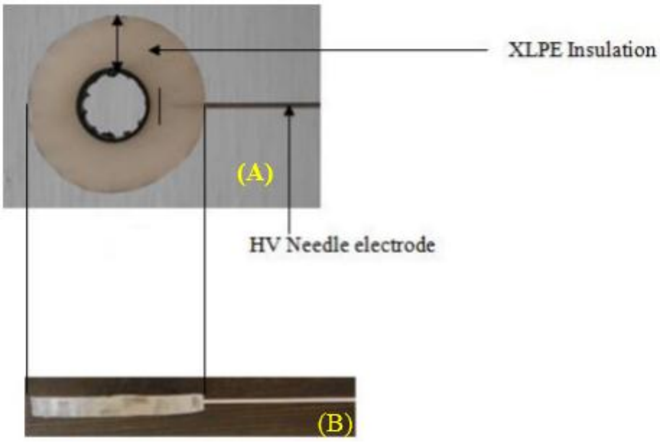


Fig. 7. XLPE test specimen with needle inserted in it (a) Cross-sectional view of XLPE test specimen (b) Side view of sample with needle electrode

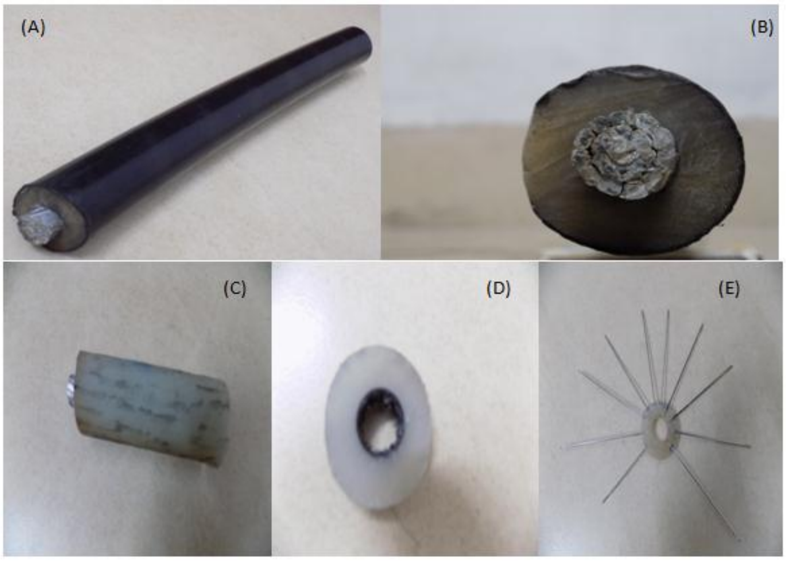


Fig. 8. Different stages of sample preparation from a 33 kV XLPE cable, (A) Specimens taken from 33 kV XLPE distribution power cable, (B) Cross-sectional view of 33 kV XLPE power cable, (C) 33 kV XLPE distribution power cable after removing the external semiconductor

4.2. PROCEDURE FOR TESTING OF XLPE POWER CABLE FOR ELECTRICAL TREE GENERATION

- All the test specimens were taken from a commercial 33 kV XLPE distribution power cable having conductors of 12mm diameter and XLPE insulation 6 mm thick (as shown in Fig. 8), these cables are used for underground distribution system.
- In the first step the outer semiconducting layer was removed leaving behind the XLPE insulation over the copper conductors.
- This unused cable was then cut into a series of disc like structures having a thickness of 3 mm and the conducting material was removed by applying little pressure on it.
- The inner semiconducting layer was also removed by the help of drilling machine, after which a hollow disc of XLPE was obtained.
- Some steel needles which are to be used as electrodes are cleaned in absolute ethanol and dried at 600 C for half an hour.
- The XLPE samples are then softened at a temperature of 1250C using a hot plate.
- The previously cleaned needle was then inserted gently into the softened XLPE sample, A sample with four needle inserted in it is shown in Fig. 8 (E).
- The samples are then cooled down to room temperature naturally.

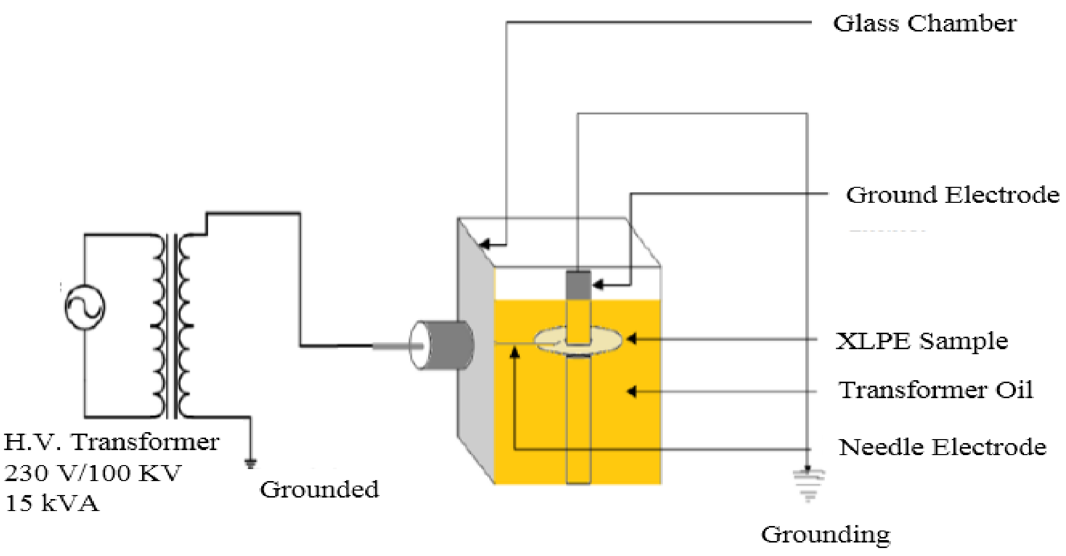


Fig. 9. Schematic diagram of experimental set up for generation of electrical tree in XLPE

As shown in the diagram the sample was subjected to voltages of different amplitude and a constant frequency of 50 Hz signal. An average of five samples was tested at each voltage level .All the tests were performed at room temperature. In this experiment our main objective is to investigate the inception of treeing in XLPE cable insulation.

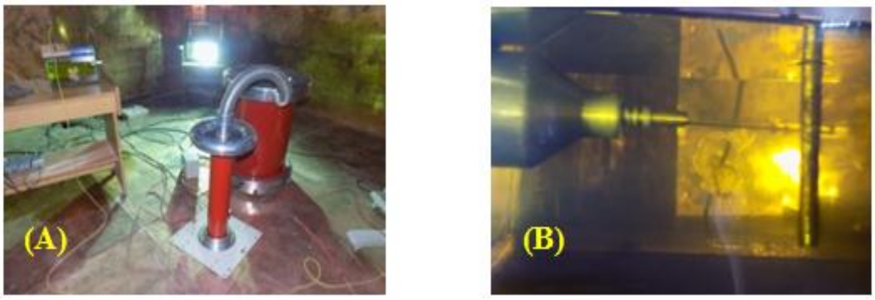


Fig. 10. Test set-up for condition monitoring of XLPE sample (A) Experimental set-up for generation of Electrical Tree under laboratory condition (B) Needle –plane arrangement emerged in side transformer oil

There are two methods to produce treeing under laboratory condition:-

The Double needle method in which two needles are inserted in opposite position and the other method is single needle method in which only one needle is inserted. In this method there is the direct ground system in which the lower part of the needle comes into direct contact with the material which is connected to the ground. In this experiment the single needle method is suitable to use.

Electrical treeing was observed by performing the above experiment. During testing the needle-plane sample was positioned in a glass container filled with transformer oil to avoid external flashover and provide light transparency. A light was placed beside the basin to observe the flash over occurring inside the insulating material. For this reason the sample was totally immersed inside the transformer oil. The main apparatus used is a wide band high voltage generator which can generate a range of voltages. An UHF sensor used for the detection of partial discharge activity was placed at a distance of 10 cm away from the sample holder, on the surface of the glass basin. The UHF sensor is a non-intrusive type sensor which can provide source of occurrence of partial discharge. One of the fundamental requirements of UHF sensor for identification of partial discharge is that it must have a broadband sensor. The output of the sensor is connected to a CRO and the voltages at which PD activity starts were noted down.

4.3. DETECTION OF PARTIAL DISCHARGE BY ACOUSTIC EMISSION METHOD

When an energy source within a material releases elastic waves rapidly and continuously, this kind of emissions is known as acoustic emission. Generally these acoustic emissions are sound waves and propagates as noise in gaseous or liquid medium like air, oil or water in the ambient pressure level. Even though a small disturbance, still it is noticeable to human ear. Analytic instruments like spectrum analyser make possible to visualise and measure acoustic signals and to understand their properties. The pressure level varied with time and frequency can be displayed graphically in an instrument called spectrogram.

4.4. ACOUSTIC EMISSION SENSOR

The acoustic signals from the electrical apparatus are converted into electrical signals by sensors. The Acoustic Emission sensor is essentially a piezoelectric crystal which transform the mechanical (compression) signal into an electrical (voltage) output.

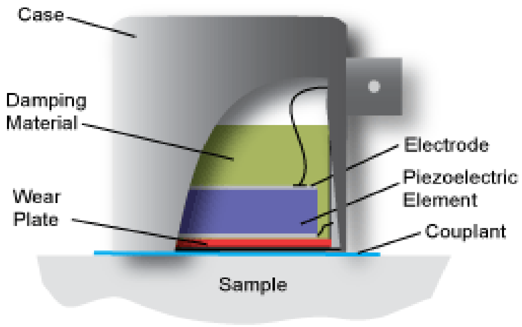


Fig. 11. Acoustic Sensor for the detection of PD signal at the time of electrical Tree growth

The piezoelectric sensor is a thin disk of piezoelectric crystal (a ceramic) metallized on both faces for good electrical contact and incorporated into a small metal cylinder to provide shielding from electromagnetic interference. The ceramics that are commonly used in AE sensors are titanates & zirconates of Barium, molded to a desired shape and fired in a high temperature kiln. Then the ceramic material is made piezoelectric by appropriate change poling. The crystal is then housed in a metal enclosure with a wear plate and a connector.

4.5. PRINCIPLE OF PD DETECTIONBY ACOUSTIC EMISSION TECHNIQUE

Partial Discharge process is the result of electron avalanche within insulating material. Due to the collision between free electrons extra energy is released which heats the material adjacent to PD region. These released energy wave propagates through the insulation medium and strikes the acoustic sensors, which receives the vibration and convert it in to electrical signals. This electrical signal can be visualise by connecting a CRO with the output of the sensor.

CHAPTER 5

EXPERIMENTS CONDUCTED ON PAPER INSULATION

- PAPER INSULATEED UNDERGROUND CABLE
- EXPERIMENTAL SET UP
- SAMPLE PREPAIRATION
- ELECTRODE GEOMETRY
- FLASHOVER PHENOMENON

CHAPTER-5

5.1. PAPER INSULATED UNDERGROUND CABLE

In paper insulated cable, conductor screens in the form of lapped metallic foils or semi-conductive carbon paper tapes are used to relieve the stress concentration which arise due to conductor standing. Moreover a metallic sheath from a lead alloy or aluminium is also used for mechanical protection of insulation which also helps to confine the electric stress within the insulation. A sheath also minimizes surface discharges, limits electrostatic and electromagnetic interference and prevents the ingress of moisture to the cable insulation.

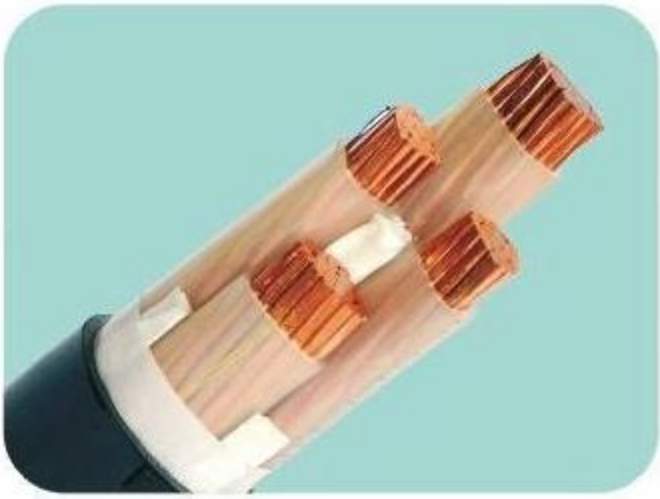
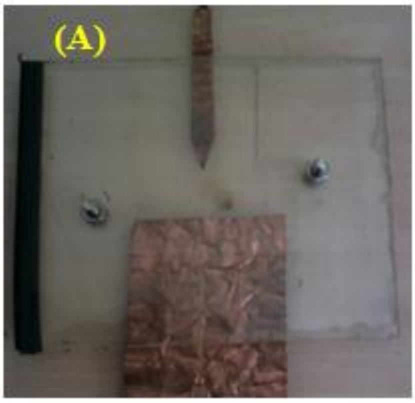


Fig. 12. Underground cable with paper insulation

Dielectric papers are produced from a variety of materials including wood, cotton, organic fibres, glass, ceramics and mica. The distinction between paper and press board is not specific but paper is generally less than 0.8 mm thick whereas boards are greater than 0.8 mm thick. The papers generally employed for insulation purpose is a special variety known as kraft paper. Low density papers are preferably used in cables. Paper is hygroscopic, therefore it has to be dried and impregnated with mineral oil or synthetic oil.

5.2. EXPERIMENTAL SETUP

The experimental setup is shown in the fig.13 . Needle –Plane electrode system is used to develope electrical tree structures and breakdown voltage measurement in paper innsulation samples.The needle as well as the plane electrode was prepaired from a polished Copper sheet. Both the electrodes are cleaned with ethanol before the application of high voltage to it. Sufficient care was taken so that there will be no scratches on the surface of the electrodes.



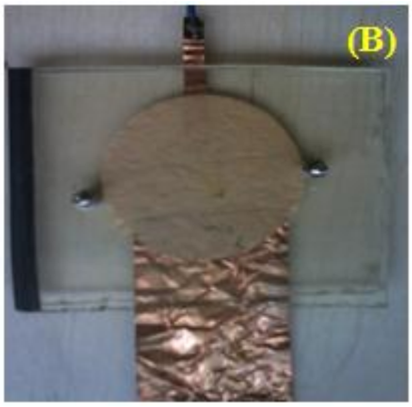


Fig. 13. Needle – Plane Electrode system (A) Without Insulation Paper, (B) With Insulation Paper

5.3. SAMPLE PREPAIRATION

The samples are taken from commercially available insulation sheets of Nomex Paper and Manilex paper insulation. Before testing it was ensured that the surface of the insulation papers are clean and dry, since the presence of any contamination or moisture on the specimen paper may affect the breakdown voltage.

5.4. ELECTRODE GEOMETRY

As shown in the Fig. 13 the needle plane electrode was kept between two sample insulation papers ,that are to be tested. The whole arrangement is than sandwitched between two acrylic sheets and both the acrylic sheets are tighten with nut and bolt arrangement. Distance between the high voltage and ground electrode were varied for different samples.

The total arrangement is then checked thoroughly before application of high voltage to it. The needle electrode is supplied with high voltage and the plane electrode is connected to the ground.With a varying distance between needle and plane electrode the brakedown voltage was studied with diffrent AC voltage conditions.

5.5. FLASHOVER PHENOMENON

The partial discharge phenomenon and the leakage current between the high voltage and ground electrode causes sparking and flashover to occur in side the insulation. For a varying insulation distance of 0.5 mm to 2 cm, flashover occur between 8-13 kV. It appears like a lightening stroke and releases light, sound and a large amount of gases.

5.6. SCANNING ELECTRON MICROSCOPE

Scanning Electron Microscope in the combination of microscope with a camera, a focused beam of electron scan the test specimen to produce image of its surface topology and to study it’s composition.

Fig. 14. Photograph of Scanning Electron Microscope

The electronic console and the electron column are the two major constituent of this instrument. The electronic console provides control knobs and switches that allow for instrument adjustments such as filament current, accelerating voltage, focus, magnification, brightness and contrast. The FEI Quanta 200 is a state of the scanning electron microscope that helps using a computer system in conjunction with the electronic console building it needless to have massive console that companies control knobs, CRTs, and an image capture device. Whole of the basic controls are retrieved through the computer system using the mouse and keyboard. The only need is to be accustomed with the GUI or software that controls the instrument. The image that is produced by the SEM is usually viewed on CRTs located on the electronic console but, instead with FEI the image can be seen on the computer monitor. Images that are captured can be saved in digital format or printed directly.

5.7. FIELD EMISSION SCANNING ELECTRON MICROSCOPE

The FESEM facilitates ultra-high resolution micro structural characterization and analysis of insulation, ceramic and metallic samples. FESEM provides elemental and also topographical information at magnification of 10 X to 300,000 X with unlimited depth of field. FESEM produced clear, less distorted image with spatial resolution 1.4 nm @ 1 kV with compared to SEM.

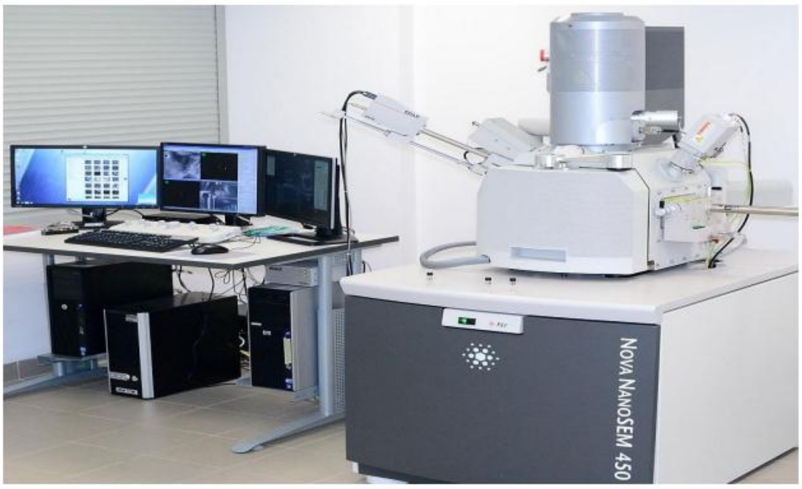


Fig. 15. Photograph of Field electron scanning electron microscope

5.8. APPLICATION OF FIELD EMISSION SCANNING ELECTRON MICROSCOPE

- Can examine the elemental composition and structure of the material
- Cross-sectional analysis of film thickness and construction details of semiconductor device.
- Analysis of surface topology of test samples in nano meter range.

CHAPTER 6

RESULT AND DISCUSSION

- TREE INCEPTION VOLTAGE IN XLPE
- INFLUENCE OF NEEDLE TIP SHARPNESS ON BREAKDOWN TIME
- RELATION BETWEEN INSULATION DISTANCE & BREAKDOWN TIME

CHAPTER-6

6.1. TREE INCEPTION VOLTAGE IN XLPE

The needle-plane electrode arrangement is shown in the Fig. 7. Both the electrodes are made up of iron. The needle electrode has a diameter of 1mm and the needle tip radius varies from 1μm to 5μm. The needle plane gap (insulation distance) was varied between 0.5 mm to 5mm. A 50 Hz AC supply was given to the test sample immersed in side transformer oil. A number of samples are tested under different voltage conditions. The magnitude of applied voltage and the duration of voltage application for each sample was noted down. The test samples are then taken out of the insulation oil, Presence of electrical tree was checked by examining the sample under Scanning Electron Microscope (SEM) to obtain the tree inception voltages. It can be said that the tree has incepted when a branch of 10μm appeared. Partial discharge was also measured during the experiment but no PD signals were obtained below the inception voltage or previous to the inception of treeing.

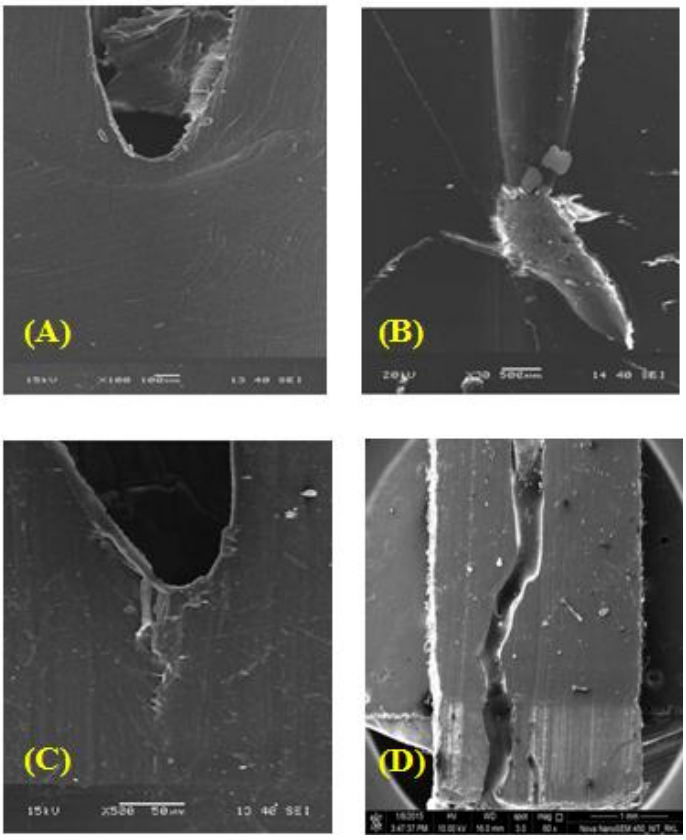


Fig. 16. Different stages of electrical tree(A) SEM observation of a XLPE sample without any voltage stress (B)Initiation of electrical tree (C) Propagation of electrical tree and (D) Break down of XLPE sample due to electrical tree

Fig. 16 (A) shows the SEM observation of a healthy sample of XLPE test specimen when the needle-plane separation distance was 2mm and there is no voltage applied to it. Fig. 16 (B) shows the initiation of electrical tree in a test specimen stressed at an AC voltage of 7 kV, this voltage is the inception voltage for an insulation distance of 2 mm. The propagation of electrical tree at a voltage of 10 kV for the same insulation distance is shown in Fig. 16 (C). Breakdown of the XLPE sample took place when a voltage of 17.5 kV was applied to the sample for a time duration of 20 min. Fig. 16 (D) shows breakdown of the insulation i.e. tree bridging the needle and the plane electrode.

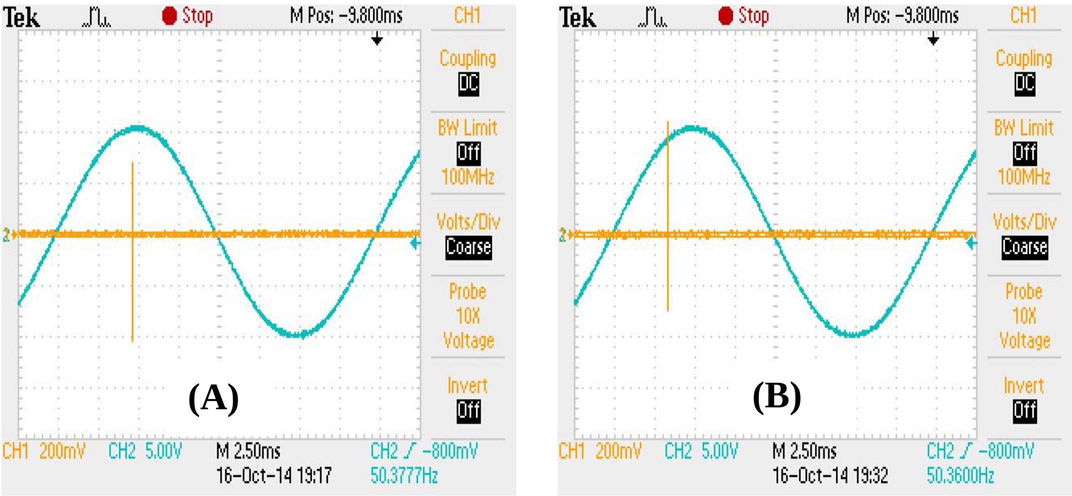


Fig. 17. PD signal obtained during testing for electrical tree growth in XLPE with needle plane distance (A) at 1 mm, (B) at 1.5 mm

Fig. 17 (A) shows the PD pulses obtained during the inception of electrical tree and the inception voltage obtained was 7 kV. The PD pulse obtained during propagation of electrical tree is shown in Fig. 17 (B). Magnitude of PD signal increases with the increase in applied voltage.

6.2. INFLUENCE OF NEEDLE TIP SHARPNESS ON TREE INCEPTION VOLTAGE

The tree inception occurs due to the accumulation of localised free electrons inside the material. In order to inspect the way in which electrical tree inception voltage varies in accordance with the needle tip radius r, experiments with the same procedure was performed using needle electrode with varying tip radius.

TABLE 6.1

Variation of breakdown time with needle tip diameter, Insulation Distance = 2mm

SL No.	Needle Tip Diameter (μm)	Applied Voltage (kV)	Time for breakdown (min)
1	1	9	1.5
2	4	9	5
3	7	9	9
4	10	9	20

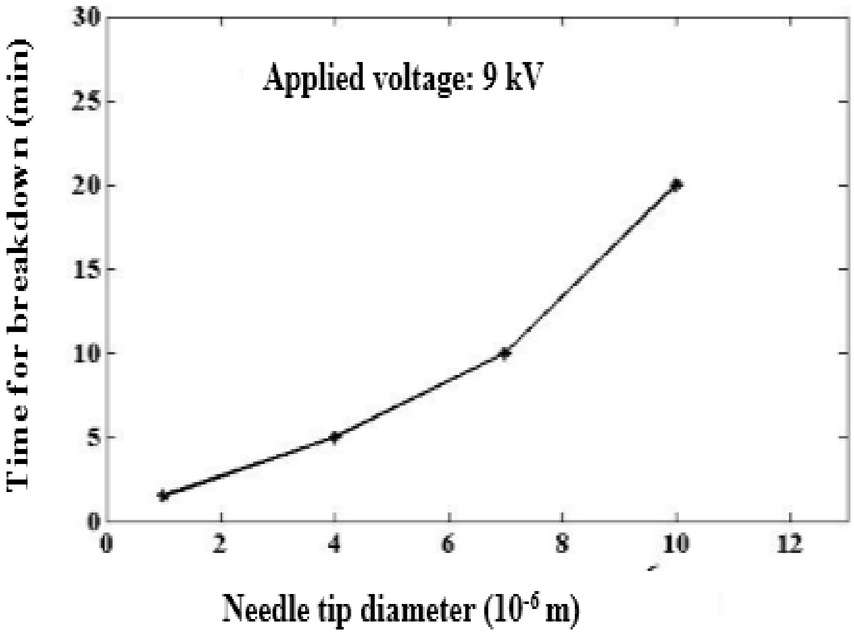


Fig. 18. Plot between needle diameter and time for breakdown

The preparation of sample and arrangement of needle and plane electrode were same as shown in the Fig. 8 and Fig. 9 respectively. Radius of the needle electrode was 0.5 mm and different needle with a tip radius of 1, 4, 7 and 10 μm were used. The applied voltage was varied between 5 kV to 35 kV. The values of voltage and time are shown in Table 6.1 and the plot between needle diameter (D) and time for breakdown (t) is shown in Fig. 18.

Five sets of samples with the same insulation distance and needle tip radius ‘r’ are taken under observation, deviations were rather large but the average values for each needle tip radius are considered. It is evident from the observations that tree inception voltage is directly proportional to the needle tip radius i.e. as the tip radius goes on increasing, inception voltage for that same sample also increases.

6.3. RELATION BETWEEN INSULATION DISTANCE AND BREAKDOWN TIME

To investigate the relation between insulation distance and breakdown time, the electrical tree inception voltage was measured in XLPE by the help of needle – plane electrode arrangement with a constant needle tip radius of 3 µm. But the insulation distance between the high voltage electrode and the ground electrode was varied in the range of 1 to 10 mm during the experiment. The result obtained is shown in Table.6.2 and the plot between insulation distance (d) and tree inception voltage (E) is shown in Fig. 19.

Table 6.2
Variation of breakdown time with Insulation distance

SL No.	Insulation Distance (mm)	Applied Voltage (kV)	Time for breakdown (min)
1	2.0	10.0	15.00
2	2.5	10.0	18.00
3	3.0	10.0	22.33
4	4.0	10.0	26.50
5	4.5	10.0	30.00

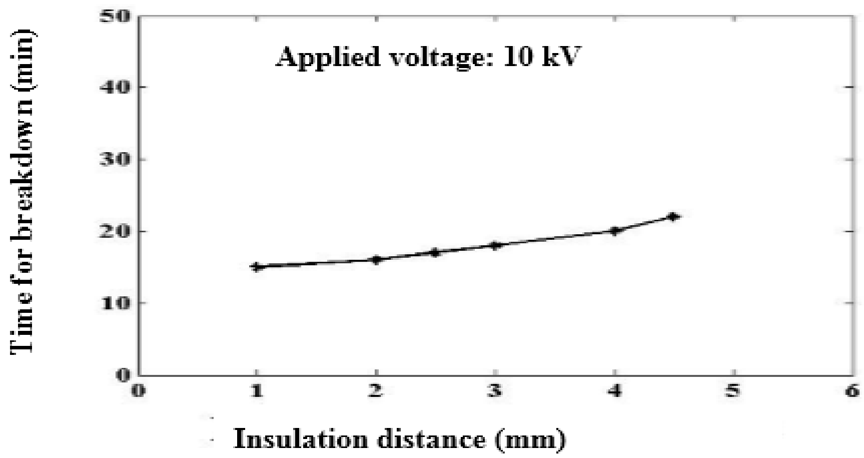


Fig. 19. Plot between insulation distance and time for breakdown

From all the obtained data it is fairly understandable that the inception voltage for electrical tree was not very large even when the insulation distance (d) was increased. From these results it is evident that treeing depends upon the sharpness of the impurity present inside the insulation as well as the insulation distance, but the dependency is less for insulation distance. The graph between insulation distance and inception voltage is almost linear.

6.4. MONITORING THE STATE OF PAPER INSULATION

When high voltage was applied to a healthy insulation paper for the very first time, PD signals are observed when the applied voltage is equal to or above the inception voltage. If the voltage is increased gradually sparking and flashover phenomenon was observed at the break down voltage. This situation could not sustain for more than few seconds, because even after a small flash over the deposited carbon trace over the insulation provide a path for leakage current thereby decreasing the electric field.

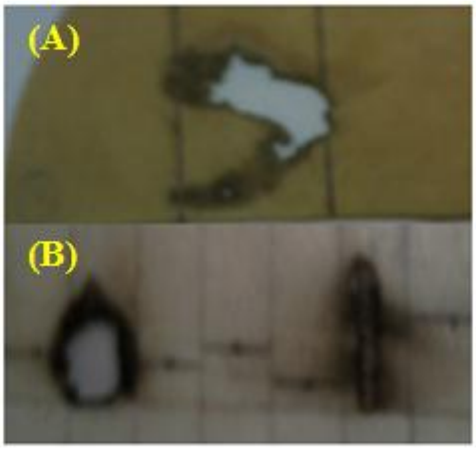


Fig. 20. Insulation paper samples after breakdown (A) Manilex paper sample after break down (B) Nomex paper sample after break down

Fig. 20 shows picture of Nomex and Manilex insulation paper with carbon trace deposited on it. Carbon deposition on the surface of paper starts when voltage is applied to the needle electrode for a time duration of more than 10 hours. The insulation paper was able to withstand the applied voltage for few more minutes if there is no carbon deposition on the surface during the first sparking. When the magnitude of leakage current increases the channel connecting the needle plane electrode got burnt giving rise to tree like channels from the periphery.

In this present work, five identical samples were tested to study the failure rate of that particular insulation due to growth of electrical trees in it. The same experiment was conduct at different voltages. Specimens are tested for increasing voltage levels one after another and the failure time was noted down. Ten failure times were noted down and after the experiment these samples were cut and visually examined under Scanning electron microscope (SEM).

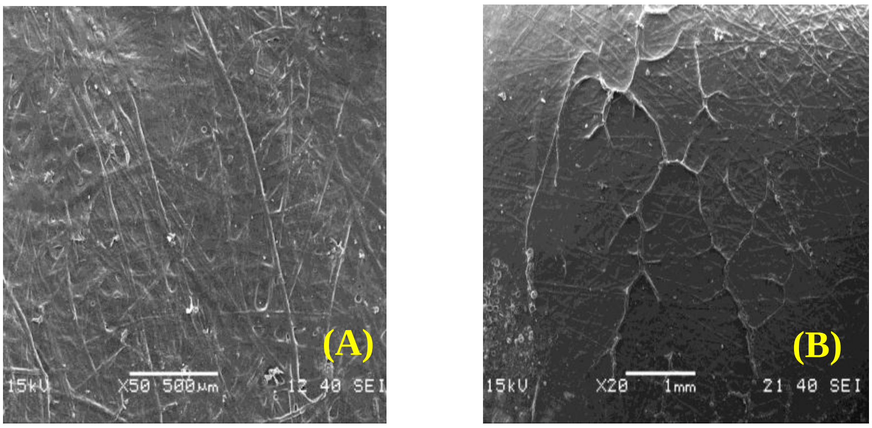


Fig. 21. Nomex paper before and after application of voltage (A) A healthy sample of Nomex paper insulation (B) Nomex paper stressed at 5 kV at an insulation distance of 4mm

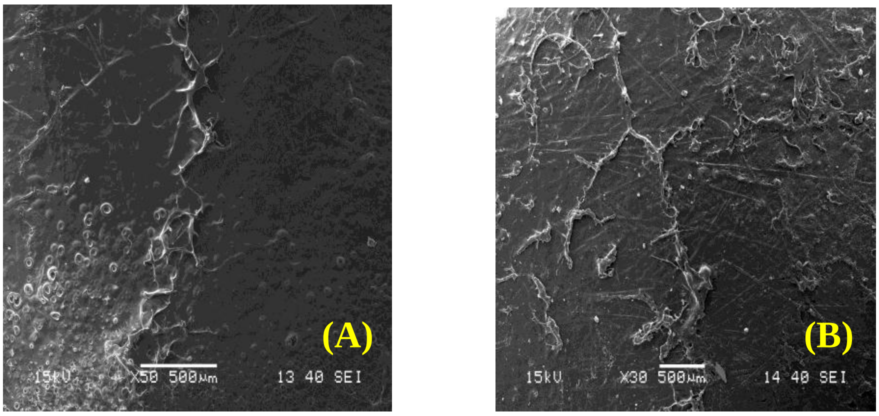


Fig. 22. Comparison of different paper samples stressed at same voltage (A) Manilex paper stressed at 10 kV at an insulation distance of 2 cm for 30 min (B) Nomex paper stressed at 10 kV at an insulation distance of 2 cm for 30 min

Fig. 21 shows a healthy sample of Nomex paper which is stressed at 5 kV for an insulation distance of 4 mm.The main channel connecting the needle and the plane electrode got burnt due to the flash over occurred during breakdown, but the type of discharge can be recognised by visualising the tree pattern originating from the main channel. Fig. 22 shows the compairison between Manilex and Nomex paper insulation for the same insulation distance and applied voltage. From the pictures it is clearly seen that the deterioration taken place in Nomex paper is more then the Manilex paper. Consequently Manilex paper insulation is suitable for high voltage applicatins.

6.5. THE PD FEATURE OF SPECIMENS

It is well known that cavities and contaminants inside the solid insulating materials are the main sources of PD. These cavities are essentially gas-filled and can result from many causes. If the voltage between the electrodes is raised to the point that the field within the cavity goes above the breakdown strength for the gas within the cavity, a PD can take place that may ultimately lead to breakdown. The time taken for breakdown to occur depends on the applied voltage and the size of the cavity.

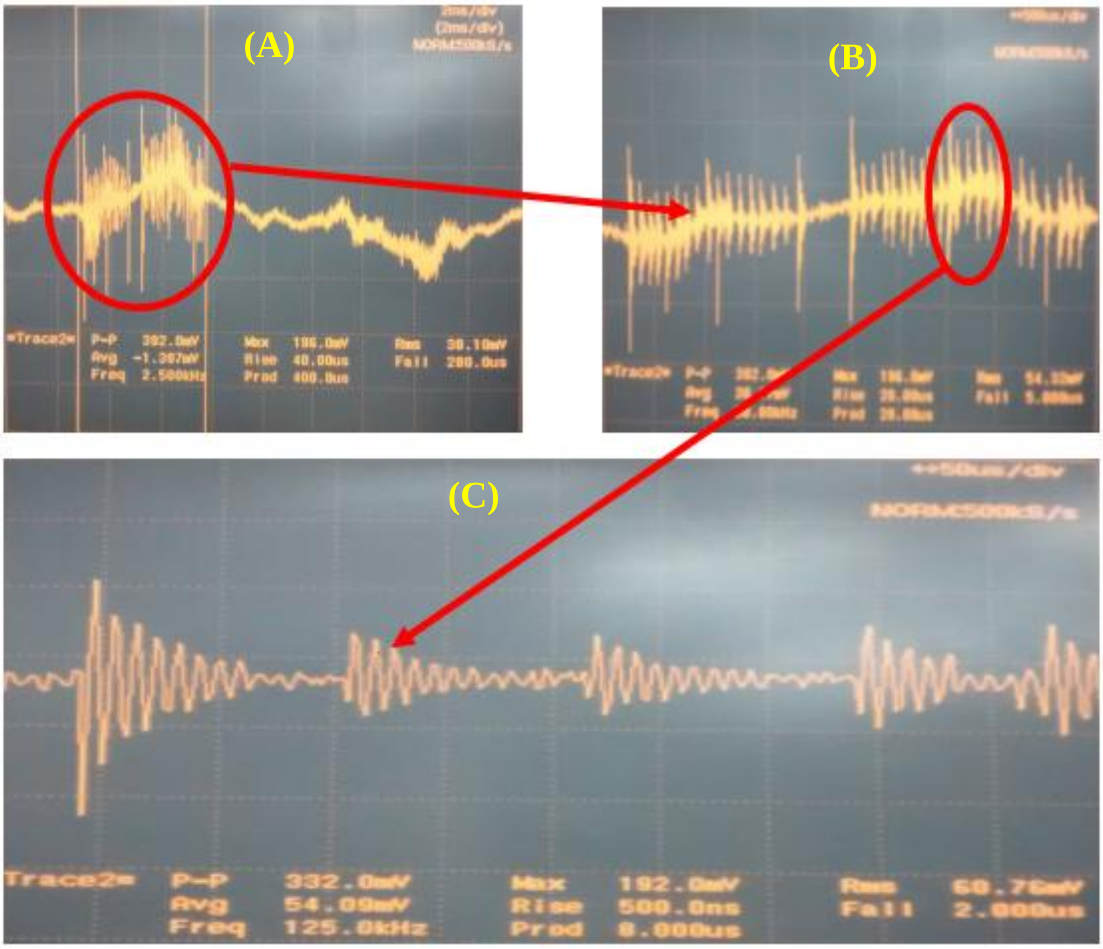


Fig. 23. Recorded partial discharge signal during the ageing process in Manilex insulating paper at a voltage of 5.6 kV . (A) Multiple partial discharge pulse appears during the test. (B) All PD pulses are zoomed together. (C) Four consequtive actual PD Pulse shape with 50 micro second width.

The partial discharge phenomenon was gradually stronger more and more with time. PD process was slow till the applied voltage came up to 5 kV for an insulation distance of 1 cm in Manilex paper. The PD process as well as the magnitude increases rapidly when the voltage range was between 6 to 6.5 kV. Break down of the specimen occur after 6.5 kV had been applied to it for 10 minutes. The PD patterns obtained is shown in Fig. 19. It was found that the shapes of PD patterns are similar throughout the range of applied voltage.

CHAPTER 7

CONCLUSION AND SCOPE FOR FUTURE WORK

- CONCLUSION
- SCOPE FOR FUTURE WORK

CHAPTER-7

7.1. CONCLUSION

The major insulations used in medium voltage underground cable system are either oil impregnated paper insulation or XLPE insulation. Several other insulations are also used in some special cases, but XLPE and paper insulations are the common insulation types and are used extensively.

- Quality of insulation depends on the no. of voids and impurities present inside the insulating material, so for different samples of solid insulation the break down voltage may vary for a specific needle plane gap.
- Propagation speed of electrical tree increases with increasing applied voltage.
- From the experimental data obtained it is clear that applied voltage is directly proportional to the separation distance between the needle and the plane.
- Different shapes of tree formed at a fixed needle plane separation and at same voltage implies the non-uniform distribution of electric field between the two electrodes.

7.2. SCOPE FOR FUTURE WORK

In the present study condition monitoring of XLPE and oil-paper insulation is done by high voltages to the insulation through needle – plane electrode. This study is helpful to examine the pattern of electrical tree structure formed inside the insulation at different conditions. Furthermore research can be carried out in this area

- Condition based monitoring for predicting the effect of frequency and temperature change on the growth structure of electrical tree.
- To use artificial intelligence to simulate electrical tree structure and to diagnose faults in that insulation.
- Performance of the insulation samples can be compared by conducing ageing tests by providing artificial ageing conditions and comparing it with the new test samples.
- In a real system degradation of oil paper insulation system also depends upon the insulation oil in use. Combined study of the degradation of oil paper as well as oil insulation should be carried out in future.

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